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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The research reported here is directed towards an understanding of solar wind-magnetosphere interactions and astrophysical plasma phenomena. Since approximately twenty-five (25) scientific papers were produced during the tenure of this contract we give here a complete list of the papers (by title and journal) produced during this contract together with abstracts where available (two of the papers were papers presented at conferences, and one is an invited review of others' work; for these we do not deem it worthwhile to give abstracts). In → see p.

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essence the research can be divided into three catagories. First, some of the basic plasma physics of the cosmic rays transported to Earth has been considered in order to ascertain the behavior of such particles under the diverse conditions which obtain in the interplanetary medium. Second, there is the sequence of papers dealing with the propagation through, and reflection from, differentially moving media. The motivation here was originally suggested by the escape of radiation from pulsar magnetospheres but the problem is of more general interest. It has application to radar backscatter from the ionosphere, and to radiation passing through both the interplanetory medium and the magnetosphere. Finally there is the work on the pair production in strong magnetic fields which is a process often invoked to account for the observed emission from pulsars. There are also several isolated papers dealing with miscellaneous topics. Of these the work on blast wave theory applied to supernova remnants has progressed considerably further since our early work on the subject reported here under the category of "Papers to be published."

During the three years covered by this contract the prime investigator has published the following papers:

1. On the Propagation of Magnetic Disturbances in the Solar Wind, Astrophys. Sp. Sci. 34, 309, 1975.

2. Reflection and Refraction of Light from a Moving Block of Glass, Phys. Rev. D, 11, 740, 1975.

3. On the Relativistic Theory of Electromagnetic Dispersion Relations and Poynting's Theorem, Ap. J., Suppl. Series, 29, 113, 1975.

4. On the Passage of Radiation through Inhomogeneous Moving Media XII. Polarized Waves in a Plane Sheared Medium (with M.A. Lee), Ap. J. 198, 477, 1975.

5. On Particle Acceleration and Radiation Output in Stochastic Electromagnetic Fields, Astrophys. and Sp. Sci. 36, 205, 1975.

6. Parametric Conversion and Amplification of Light in Moving Media, Astrophys. and Sp. Sci. 35, 363, 1975.

7. On Galactic Rotation and the Intergalactic Medium (with R. Cowsik), Ap. J. 199, 555, 1975.

8. On the Diffusion of Light in Turbulent Shearing Media, Ap. J. 199, 734, 1975.

9. On Pair Production in Intense Electromagnetic Fields Occurring in Astrophysical Situations (with J. K. Daugherty), Astrophys. and Sp. Sci. 38, 437, 1975.

10. On a Curiosity Arising from Fizeau's Experiment, Am. J. Phys. 43, 910, 1975.

11. Random Function Theory Revisited: Exact Solutions Versus the First Order Smoothing Conjecture (with E.N. Parker), J. Math. Phys. 16, 1838, 1975.

12. A Variational Principle for Cosmic Ray Transport Equations, 14th International Cosmic Ray Conference (Munich, August 1975), Paper MG 1-11, Conference Proceed-ngs Vol. 3, 881, 1975.

13. The Effect of Interplanetary Discontinuities on the Angular Distribution of Energetic Particles. 14th International Cosmic Ray Conference (Munich, August 1975), Paper SP 5.3-1, Conference Proceedings Vol. 5, 1807, 1975 (with K.C. Hsieh, Y. C. Lin, and J. D. Sullivan).

14. Projections, Reconstructions and Orthogonal Functions (with E. Zeitler), J. Math. Anal. and Appl., (November) 1976.

15. On Radiation Production in a Sheared Medium. Astrophys. and Sp. Sci. 41, 387, 1976.

16. On Conserved Quantities in Kinematic Dynamo Theory. J. Math. Phys. 17, 17, 1976.

17. Some Simple Limits on Size and Rotation Speed of Astrophysical Objects Emitting by Accretion. Astrophys. and Sp. Sci. 43, 91, 1976.

18. Theory of Pair Production in Strong Electric and Magnetic Fields and its Applicability to Pulsars (with J. K. Daugherty). Phys. Rev. D. 14, 340, 1976.

19. Review of "A Unified Approach to Mean Field Electrodynamics" (by P. H. Roberts and A. M. Soward, Astronom. Nach. 296, 49-64, 1975) in Math. Rev. 53, 2148, 1976.

In addition, the following papers have been accepted for publication but have not yet appeared in print:

20. Relativistic and Non-Relativistic Gas Flows in Astrophysical Media: The General Symmetric Solution in the Low Pressure Limit. Astrophys. and Sp. Sci. 1976.

21. Mathematical Theory of Isothermal Blast Waves and the Question of their Applicability to Supernova Remnants (with V.M. Vasyliunas). Ap. J., November. 1976.

22. Concerning Viscid and Inviscid Self-Similar Blast Waves: Spherical, Isothermal Flows and Inferences for Supernova Remnants. Astrophys. and Sp. Sci. 1977.

Further, the following papers have been submitted for publication but we do not yet know if they have been accepted for publication:

23. "On the Momentum Carried by Sound Waves", submitted to Phys. Rev.

24. "The Fizeau Effect: Theory, Experiment and Zeeman's Measurements", submitted to J. Appl. Phys.

25. "On Pulsar Driven Isothermal Blast Wave Models of Supernova Remnants", submitted to Astrophys. and Sp. Sci.

26. "Isothermal Self-Similar Blastwave Theory of Supernova Remnants Driven by Relativistic Gas Pressure", submitted to M.N.R.A.S.

27. "On Phase and Ray Directions of Magnetosonic Waves", submitted to J. Plasma Phys.

Abstracts of papers 23 through 27 are not included for they do not represent work which is either published or accepted for publication.

In addition, work on a further three papaers is nearly complete and acknowledgement for funding received under contract F-19628-75-C-0101 will be made in these papers when, and if, they are published.

Also the student, Philip Isenberg, finished his thesis work on the stability of adiabatic self-similar blast waves as applied to supernova remnants. A version of this thesis has been submitted for publication to Ap. J.

We now give the abstracts of the published papers 1 through 19 (with the exceptions of papers 12, 13, 17 and 19 for which reprints are not available) since they represent the main lines of research which have been investigated over the last two years.

On the Propagation of Magnetic Disturbances in the Solar Wind

Under the geometrical optics approximation we discuss the propagation of a polarized magnetic profile, made up of Alfven waves, in the solar wind. We show that (i) the profile propagates at an angle to the radial direction (the direction of the solar wind flow), (ii) the radial half-width of the profile stays essentially constant, or even diminishes a little, with distance from the Sun, (iii) the half-width in a direction transverse to the radial direction increases without limit as the magnetic profile moves outward from the Sun. Thus the profile stretches out into a 'ribbon' which could, of course, be experimentally identified as a discontinuity. We also give equations for the variation of polarization of the profile, and illustrate the behavior of polarization in a simple case.

We have done these calculations to show that the production of 'discontinuities' in the solar wind can arise from propagation effects on irregularly shaped 'blobs' of magnetic field, as well as from other causes.

Reflection and Refraction of Light From a Moving Block of Glass

For a block of glass moving with speed βc we present calculations which give the changes in the laws of reflection and refraction of light from the laws which hold when $\beta = 0$. In particular we show (i) that changes in the critical internal reflection condition, although formally of order β^2, are obtainable by measuring the refraction angle to $O(\beta)$; and (ii) that the reflection coefficient depends not only on the polarization plane of the incident light but also on whether the plane of incidence does, or does not, include the direction of motion of the glass block. For instance, for light incident in a plane perpendicular to the direction of motion there is no Brewster

angle for either plane of plarization, while for light incident in a plane containing the direction of motion at least one (and sometimes *both*) planes of polarization possess a Brewster angle. We have done these calculations in order to demonstrate that the shearing of one's medium relative to another can have profound effects on the reflection and refraction of light. A major point here is that even when it might appear *a priori* that O (β^2) phenomena are unobservable in the laboratory, the present calculations show that this is not always so.

On the Relativistic Theory of Electromagnetic Dispersion Relations and Poynting's Theorem

Constitutive relations, and general dispersion relations, are derived for an arbitrary, anisotropic, dispersive and dissipative medium which is moving relative to an inertial observer. The constitutive relations are expressed in terms of the "local" dielectric tensor, magnetic permeability, etc. where "local" refers to the instantaneous rest frame of the medium. We also give the generalization of Poynting's theorem for power flow including the expression for the rate at which the moving medium does work on the radiation. In view of the current interest in radiation generated in, and passing through, pulsar magnetospheres, we believe that the general results presented here are, perhaps, not without some astrophysical import.

On the Passage of Radiation Through Inhomogeneous, Moving Media. XII. Polarized Waves in a Plane, Sheared Medium

Using the complete set of Maxwell equations, we follow the ray paths and Stokes parameters of a ploarized wave which passes through a slab of differentially shearing material of variable refractive index. We relate the

polarization state of the signal leaving the top of the slab to the polarization state of the initial wave. In general the two are not the same. We have done these calculations to illustrate the point that the polarization properties of observed pulsar signals may be very different from those of the emitted signals due to propagation effects in the differentially shearing magnetospheres that most pulsars are believed to possess.

And while we recognize that the precise amount of polarization variation is model dependent, our calculations show that even for simple situations a noticeable polarization variation occurs. Accordingly the calculations reported here are an eduacative device: they show that it is, perhaps, unwise to assume that the observed polarization properties of pulsar signals are the same as the emitted signals.

On Particle Acceleration and Radiation Output in Stochastic Electromagnetic Fields.

We demonstrate that when charged particles interact with a plane electromagnetic wave which possesses a random amplitude, then the particles are accelerated to high energy because they are pushed along by the wave's Poynting vector. Not only are they so accelerated, as they are carried along by the wave, but also they diffuse at right angles to the direction of the Poynting flux (i.e. in the direction of the wave's electric field). The ultimate energy that such particles can reach is determined when they radiate as much energy per unit time as they receive from the plane wave. For numbers believed typical of the Crab nebula this ultimate energy is of order $10^{10}\ mc^2$. We have done these calculations to show that turbulent electromagnetic waves are quite efficient in generating high energy particles from low energy particles. Thus

when the low frequency coherent waves emitted by a magnetized rotating neutron star are turned into incoherent waves because of wave-plasma interactions in a surrounding nebula, they still accelerate particles to rather high energies. Accordingly, while it obviously takes less time to produce high energy particles with a coherent wave than with a turbulent wave, the calculations given here show that the bulk of the relativistic electrons in the Crab nebula could still be energized by the turbulent remnants of a coherent wave.

Parametric Conversion and Amplification of Light in Moving Media

We present calculations which should be or interest in connection with the problem of radiative transport through the magnetospheres of pulsars and the envelopes of quasars, where not only are particle speeds of the order of the speed of light expected, but also variations of refractive index with frequency and position.

The calculations show that by shining monochromatic light normally onto an interface between two media of different refractive indices it is relatively easy for the transmitted radiation to be spread out in frequency and of higher total intensity than the incident radiation. In asserting this we are assuming that the boundary between the two media is moving non-uniformly in time.

The two idealized examples which have been worked through to illustrate this parametric conversion and amplification mechanism are:

(i) monochromatic light passing normally through a slab of material which is bounded by two fixed transparent plates and which is accelerating parallel to the plates. The intensity of the transmitted light exceeds the intensity of the incident light by a factor $O(\gamma)$ where γ is the usual Lorentz factor.

(ii) monochromatic light, of frequency ϖ , passing normally through a

plane interface between vacuum and a medium of constant refractive index, n_1, where the interface is oscillating around some fixed equilibrium position with a maximum speed $O(c)$. In this case the transmitted intensity exceeds that which would be transmitted through an identical interface at rest by a factor $1 + (\gamma_{max} -1)\ (n_1 -1)^2$. For fixed refractive index and large γ this factor can be considerably in excess of unity. The frequency distribution of the transmitted radiation varies as $\omega^{-1/3}$ for frequencies in the range $\bar{\omega} \ll \omega \ll \bar{\omega}\gamma^3$.

Altogether, the calculations reported in this paper indicate that the production of broad-band, high-intensity radiation from relatively weak monochromatic light is a process which is likely to occur in most astrophysical objects where it is believed, or suspected, that rapid motions and spatial variations occur.

<u>On Galactic Rotation and the Intergalactic Medium</u>

The observed spectrum of the isotropic diffuse X-ray background has often been invoked to infer the possible existence of a hot intergalactic medium at a density of the order of that required for closure of the Universe. We consider here the effect of such a hot isotropic gas on the rotation of galaxies, with the coupling between the intergalactic medium and the galaxies being provided by galactic magnetic fields. The calculation provides the basis for an indirect observational test which bears on the existence of the hot intergalactic medium. We point out that the basic physics involved should also pertain to variable X-ray stars emitting by mass accretion and, perhaps, to the Coma cluster of galaxies.

<u>On the Diffusion of Light in Turbulent Shearing Media</u>

We present some simple calculations to show that a beam of light is, in

general, severely distorted and dispersed from the straigh-line path that would obtain in vacuum when passing through a medium possessing a turbulent velocity of order c, the speed of light in a vacuum. The motivation underlying these calculations is the problem of radiative transport through the magnetospheres of pulsars where particle energies in excess of about $10^8\ mc^2$ are believed to obtain.

On Pair Production in Intense Electromagnetic Fields Occuring in Astrophysical Situations

We show that the pair production rate in a strong magnetic field is substantially altered when an electric field is also included. We illustrate and emphasize this significant alteration by considering a few special cases. In the vicinity of the polar cap of a rotating magnetized neutron star it is currently thought that *both* steady electric and magnetic fields must be present. The results presented here then indicate that some considerable degree of caution must be exercised in applying pair production rates calculated under the assumption of zero electric field to the problems of pulsar emission and the gneration and maintenance of pulsar magnetospheres. In general such rates are very different from the rate computed allowing for the existence of an electric field.

On a Curiosity Arising from Fizeau's Experiment

We show that for a cold plasma moving at velocity v there is no change in the velocity of light to first order in v over that obtaining if the plasma is at rest. We also give the general dependence of refractive index on frequency in order that there be no Fizeau effect [to $O\ (v)$] for a medium in motion, and we show that this implies that the product of the phase velocity and the group velocity must equal c^2. We also give the physical reason

for the absence of the first-order Fizeau effect in terms of the local dipole polarization and the different wave frequency seen by the moving dipoles compared to the incident wave frequency.

Random Function Theory Revisted: Exact Solutions Versus the First Order Smoothing Conjecture

We remark again that the mathematical conjecture known as first order smoothing or the quasilinear approximation does not give the correct dependence on correlation length (time) in many cases, although it gives the correct limit as the correlation length (time) goes to zero. In this sense, then, the method is unreliable.

Projections, Reconstructions and Orthogonal Functions

The techniques used for reconstructing an object from its projections are set up within a general mathematical framework. We show that the simplest version of the problem involves choosing a generator for two sets of orthogonal functions, and we also give the general theory. We illustrate the power of the method by considering in detail four examples of special projections. We have done these calculations to tie together with a general theory the many different choices of orthogonal polynomial that have been used by various investigators in the problem of projection and reconstruction and to show, by specific illustration, the interconnection of these various functions.

On Radiation Production in a Sheared Medium

We give an expression for the radiation produced by a uniformly charged particle when it traverses normally a semi-infinite boundary between two media, both of the same dielectric constant; the refractive index n being measured in the appropriate rest frames of the media. The media are taken

to slip relative to each other with constant velocity parallel to the boundary.

We compute the differential power output and show that (a) the emitted radiation has a flat spectrum up to a frequency such that n can no longer be considered constant; (b) the angular dependence of the emitted radiation is peaked at an angle to the direction of motion of the particle; (c) there is a back-scattered component to the radiation. In view of the complexity of the analytic formulae for the differential power output we give some numberical examples for $n > 1$ and $n < 1$ to illustrate the different angular dependences of the power output in both cases.

Since high energy charged particles are currently thought to be produced in the magnetospheres of pulsars, and since such particles must then escape from the environment of the pulsar, by traversing the differentially shearing magnetosphere, it would seem that the simple calculations reported here illustrate a new mechanism for radiation production which is of astrophysical interest.

On Conserved Quantities in Kinematic Dynamo Theory

Using a Lagrangian approach to the magnetic induction equation in an infinite medium, we demonstrate that there exist seven conserved quantities which, by analogy with classical mechanics, we label as "energy," "momentum," and "angular momentum." For prescribed fluid motions we spell out the detailed conservation equations. For a fluid motion which is turbulent we also give the average conserved quantities. In a pragmatic sense it is expected that these conservation laws will be of use in attempts to obtain numerically accurate solutions to the turbulent kinematic dynamo equations. Since the magnetic induction equation is not self-adjoint, numberical attempts to date

have to impose some extraneous ad hoc "criteria of goodness" at any given level of numerical truncation. The conserved quantities given here provide an internal check of the accuracy of any numerical calculation without the necessity for arbitrarily imposed external criteria of accuracy. As such they should be a powerful tool in rapidly increasing the accuracy of numerical solutions to the knematic dynamo equations. We also point out that the conserved auantities can be used to indicate the possibility of kinematic dynamo activity *ahead* of any detailed calculations.

Theory of Pair Production in Strong Electric and Magnetic Fields and its Applicability to Pulsars

We give the general results for spontaneous and photon-induced pair production in strong, constant parallel electric and magnetic fields. For photons propagating exactly parallel to the constant fields there is no effect. For photons propagating at right angles to the constant fields the vacuum behaves in a birefringent manner. These results generalize earlier work in the field by others who did not include a constant electric field. Some numerical estimates are given for both the spontaneous and photon-induced pair production rates using numbers currently thought to obtain near the surface of a pulsar - which is believed to possess not only a strong magnetic field but also a strong electric field.

Relativistic and Non-Relativistic Gas Flows in Astrophysical Media: The General Symmetric Solution in the Low Pressure Limit

The dynamical expansion and motion of supernova remnants, double radio galaxies, etc., into and through the surrounding interstellar and/or intergalactic gas are processes of some importance in astrophysics for inferring energy, magnetic fields, particle pressure, etc. in a wide variety of astro-

physical situations. We are usually hampered by the fact that it is often difficult to obtain a solution to the equations describing the flow of a gas into a surrounding medium starting from a postulated equation of state. The present paper shows how, by starting with a fluid flow that one believes adequately describes the gas, it is possible to solve by quadratures for the associated pressure and density. And in making these remarks we are implicity assuming plane, cylindrical or spherically symmetric flow velocities, which may be unsteady in time. The fluid speed can be chosen to be either non-relativistic, but the method is valid only when the resulting gas pressure, $\mathcal{P}$, is small compared to ρc^2, where ρ is the mass density. We illustrate the method by solving a simple problem. In view of the ever increasing number of astrophysical situations where some measure of the fluid flow through an object is becoming available (often from Doppler shifted lines) we believe the present technique should be of some use in helping to unravel the internal dynamical properties of the flowing gas.

Concerning Viscid and Inviscid Self-Similar Blast Waves: Spherical, Isothermal Flows and Inferences for Supernova Remnants

We investigte the spherically symmetric, self-similar flow behind a blast wave from a point explosion in a medium whose density varies with distance as $r^{-\omega}$ with the assumption that the flow is isothermal and viscid. If $o < \omega < \omega_c$ where $\omega_c = 1/9\ [13 - (160)^{1/2}]$ Lerche and Vasyliunas have shown in the inviscid situation that there exist two critical points in the flow speed-radial distance plane, and that all solutions are degenerate in that they pass through the lower critical point with the same slope. The present paper shows that as the viscosity tends to zero, the viscid flow does not tend towards the

inviscid flow pattern. Now the validity of adiabatic blast wave models has elsewhere been shown to be questionable for supernova remnants, and the inviscid blast wave models have also been shown to be inappropriate for supernova remnants. Taken together with these previous results, the results of the present calculations strongly suggest that the assumption of isothermal blast wave behavior of supernova remnants, either viscid or inviscid is not valid. Since the adiabatic blast wave models have elsewhere been shown to be inappropriate descriptions of supernova remnants, it is doubtful whether the self-similar property can be invoked at all in the case of supernova remnants.